Fluid Plasma Specific Entropy in the Magnetosphere: Properties and Questions

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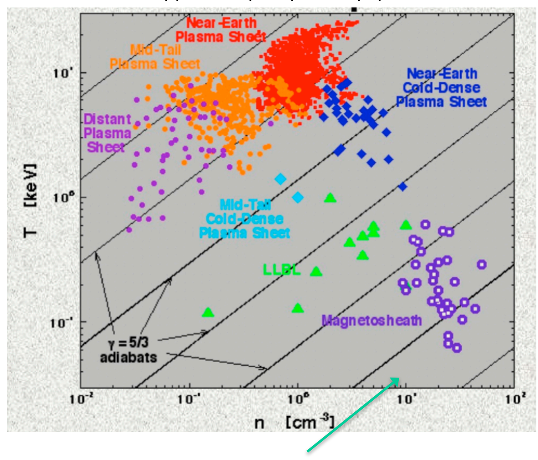
Specific Entropy

Specific entropy (p/N^gamma) is an important tracer for plasma in the magnetosphere.

Ideally, specific entropy should be conserved as plasma convects.

However, the populations in the magnetosphere differ by orders of magnitude from the magnetosheath.

Entropy density of plasma populations

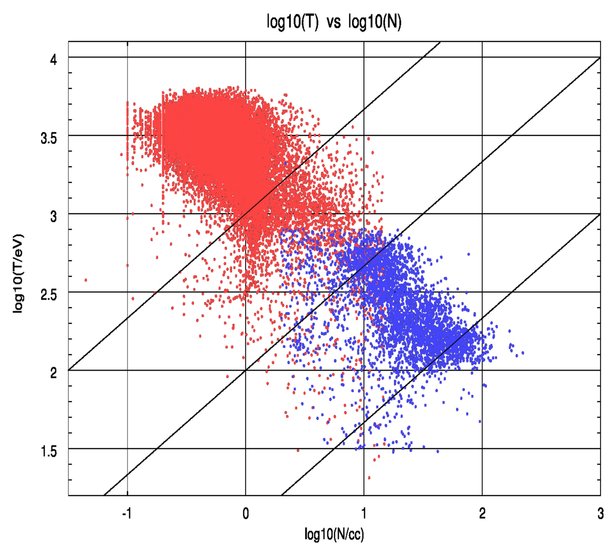


Solar wind: less dense, cooler

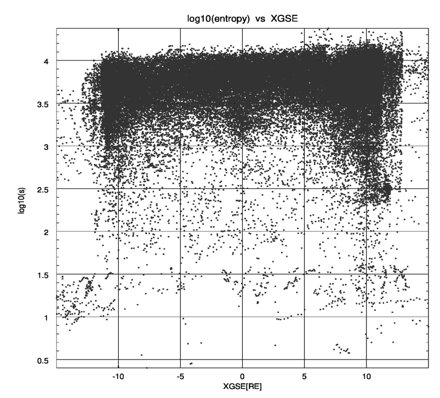
From Borovsky, GEM'06

Scatterplot redux w/THEMIS & MMS

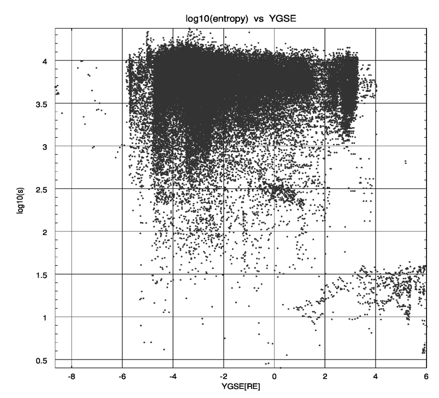
- Similar scatterplot with THEMIS and some MMS data, all 15m averages.
- Blue: MSH, red: PS.
- Some region misidentification possible.
- Not a good idea to use N, T to identify regions.
- Confirms Borovsky results.
- Why?



Plasma sheet location dependencies

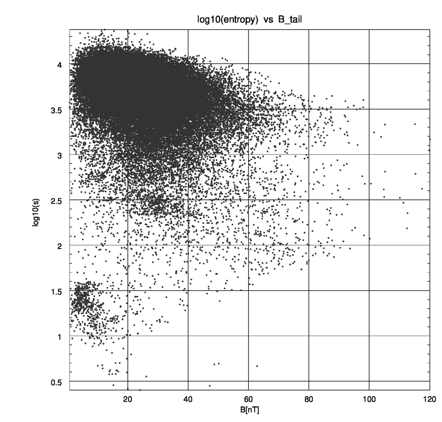


- Max entropy increases sunward.
- Possible mixing of x/y effects due to orbits.

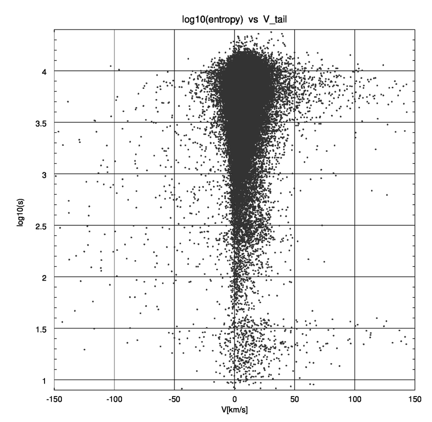


- Max entropy increases dawnward, average duskward. Needs to be normalized for orbital bias.
- Looks like there is a separate population that is magnetosheath contamination.

Some Plasma sheet B/V dependencies

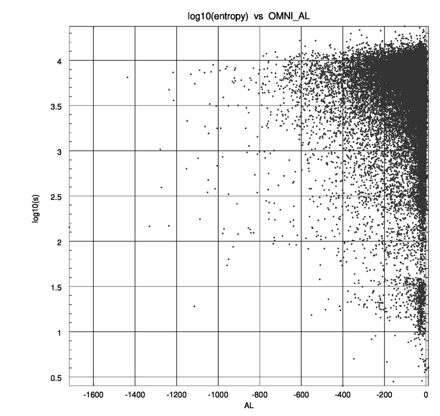


- Entropy decreases for higher B → injection of lower entropy plasma?

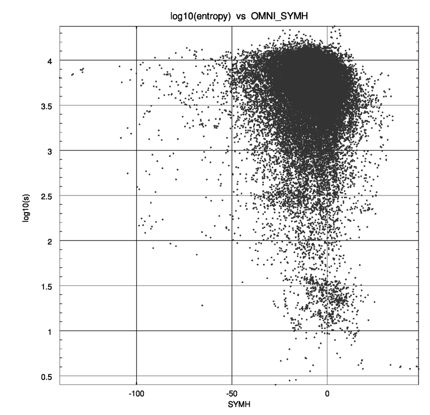


- Earthward BBFs → warm, but not too hot
- Tailward BBFs → cold
- Less averaging may give a clearer picture.

Activity dependencies

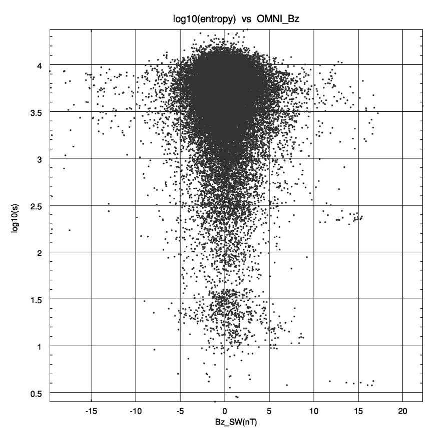


- Max entropy decreases for higher abs(AL) → BBFs/plasmoids remove high entropy plasma from tail?

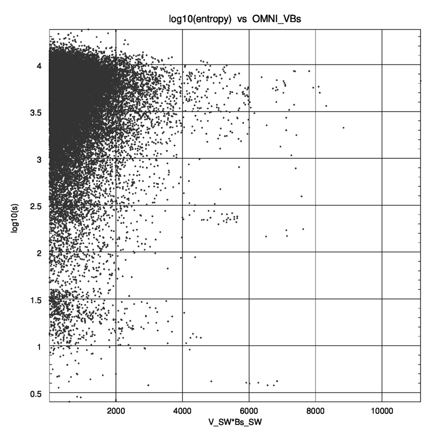


- SYMH similar to AL → lower SYMH does not imply hottest plasma.

Solar wind dependencies

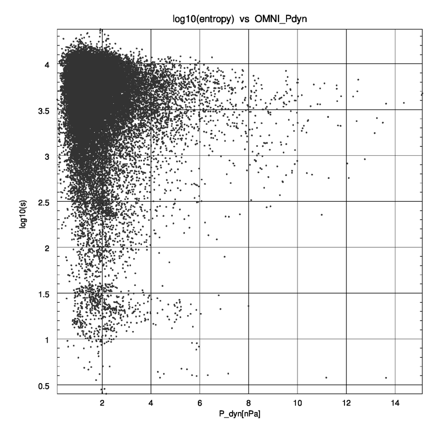


- No obvious Bz dependence.
- Including time lag may change the picture a bit.

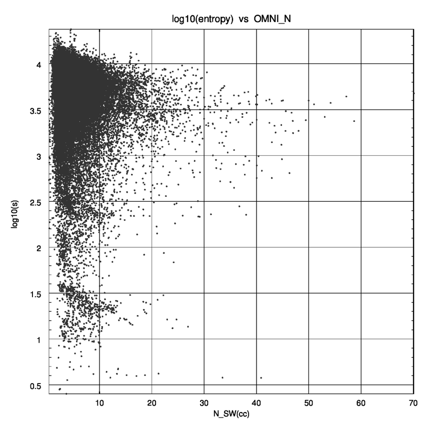


- Hottest PS for lowest driving?

Solar wind dependencies



- Pdyn acts much like Bz.



- But cooling trend even stronger for high SW density → CDPS?

What does the heating?

The energy conversion density rate E.J in ideal MHD plasma is given by

$$\mathbf{E}\cdot\mathbf{J} = (-\mathbf{v}\times\mathbf{B})\cdot\mathbf{J}$$

If resistivity η is present, this becomes

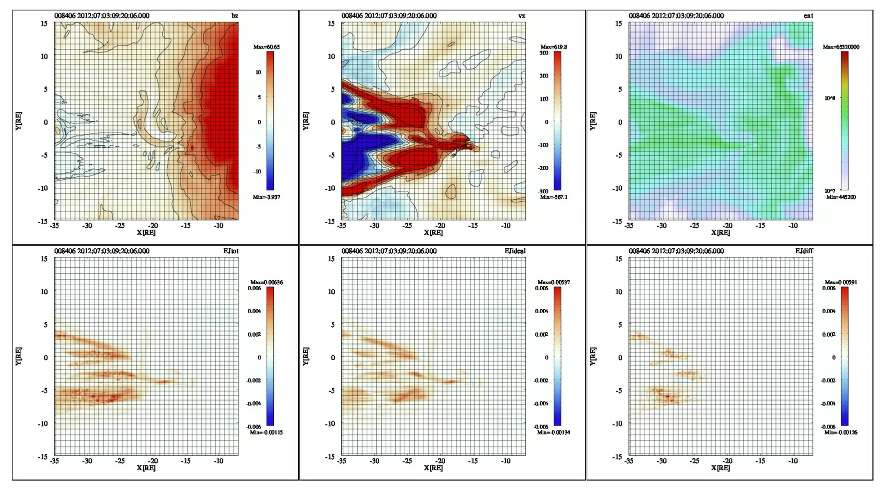
$$\mathbf{E}\cdot\mathbf{J} = (-\mathbf{v}\times\mathbf{B} + \eta\mathbf{J})\cdot\mathbf{J}$$

Which can be written as

$$\mathbf{E}\cdot\mathbf{J} = \mathbf{v}\cdot(\mathbf{J}\times\mathbf{B}) + \eta|\mathbf{J}|^2$$

The first term on the RHS is the density of the rate work done by the field on the plasma, which is reversible/adiabatic (motor/generator). The second term is irreversible Ohmic dissipation rate. We are interested in computing the latter from gridded numerical variables.

Dissipation



The full Ohm's law does not change the MHD picture

$$\vec{J}\cdot\vec{E}' = \eta|\vec{J}|^2 - \vec{U}_e\cdot(\nabla\cdot \mathsf{P}_e) + \epsilon\vec{U}_e\cdot(\nabla\cdot \mathsf{P}_i) + \vec{U}_e\cdot\nabla\cdot(\rho_e\vec{U}_e\vec{U}_e - \epsilon\rho_i\vec{U}_i\vec{U}_i).$$

- All terms on the RHS are reversible, except for the collisions (expressed as a resistivity).
- Thus, reconnection is not likely to produce entropy.
- Slow mode shocks could do the trick, but they are rarely observed, and Otto showed that for prevailing tail parameters they can hardly produce much entropy.

Hypothesis I:

- Plasma is heated as it enters the magnetosphere through current sheets, Kelvin-Helmholtz waves, or diffusion.
- Consistent with some observed properties. For example Kelvin-Helmholtz activity should increase with northward Bz and high SW dynamic pressure.
- East-West asymmetries could give some hints. Needs more careful correlation w/SW parameters.
- Could also be tested with MHD simulations.

Hypothesis II:

- During quite and moderately disturbed times the plasma sheet acts like a slow cooker, constantly churning and slowly dissipating energy.
- This may be EM power or flow energy dissipation in some some sort of viscous interaction, probably at the end of the turbulent cascade.
- During active times the tail rids itself of the extra internal energy by expelling plasmoids & tailward BBFs, and by injecting low entropy plasma into the inner magnetosphere or convecting it out to the dayside. Note that low entropy is required for DFs to penetrate close to Earth.
- Not consistent w/modeling results, but model does not contain all the physics.

Energy conversion in MHD Codes

In numerical codes two electric fields can be distinguished. The first is the motional electric field:

$$\mathbf{E}_M = -\mathbf{v}\times\mathbf{B}$$

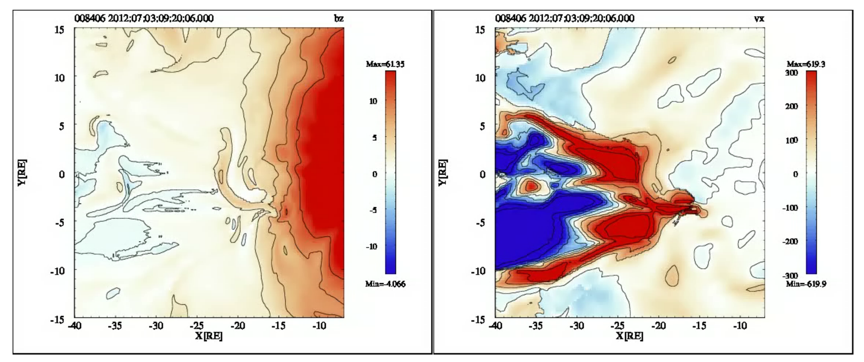
The second is the numerically calculated field $\mathbf{E}_N$ that includes any applied resistivity terms along with numerical resistivity. The latter comes from finite difference errors, upwinding, flux limiters, and other methods that are used to keep the numerical scheme stable. The true dissipation in the code can then be extracted using the difference of these fields:

$$\mathbf{E}\cdot\mathbf{J}\big|_{\text{diss}} = (\mathbf{E}_N - \mathbf{E}_M)\cdot\mathbf{J}$$

There are some subtleties involved because the fields are on different grids, but different interpolation schemes give basically the same results.

BBF/DF Activity in the Tail Current Sheet

- OpenGGCM simulation of 2012/07/03 substorm.
- Values taken at z(Bx=0).
- Most reconnection sites between x=-35 and x=-25 and flow channels are ~2-4 RE wide.
- Every BBF has a DF associated with it and some BBFs have a negative Bz precursor.
- Many DFs have a convex (mushroom-like) shape, but that is not universal.
- The dawn bias is in disagreement with THEMIS statistics (Imber et al., 2011).



Summary and Conclusions

- OpenGGCM simulations show Bursty Bulk Flows (BBFs) and Dipolarization Fronts (DFs) similar to those observed.
- At the DFs plasma is compressed and heated, but the heating is adiabatic and dissipation is negligible.
- Dissipation of field energy occurs primarily near the reconnection x-lines and part of the reconnection exhaust close to the x-lines.
- Two hypotheses proposed, but so far no strong evidence for or against either of them.